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Measurements of solar radiation and illuminance on vertical surfaces and daylighting implications

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Abstract

There is a growing concern about the rapid development of infrastructure and building projects and their likely impacts on the environment. Particular concerns have been raised about office building developments and energy consumption issues. In recent years, there has been increasing interest in using daylight to save energy in buildings. Lighting control integrated with daylighting is recognised as an important and useful strategy in terms of energy-efficient building design. It is believed that proper daylighting schemes can help reduce the electrical demand and contribute to achieving environmentally sustainable building developments. This paper presents a simple method for estimating the likely energy savings in electric lighting due to daylighting and the possible cooling penalty. Vertical solar radiation and illuminance data measurements are described. Cumulative frequency distributions of daylight availability are reported. The likely energy savings in office buildings are determined based on on–off and top-up controls, and the energy and environmental implications are discussed. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Solar radiation and illuminance measurements; Vertical surfaces; Daylighting; Energy savings; Air-conditioned office buildings

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1. Introduction

Daylighting is an important factor in interior design affecting the functional arrangement of spaces, occupant comfort (visual and thermal), structure, and energy use in buildings. The amount of daylight entering a building is mainly through window openings which provide the dual function not only of admitting light for indoor environment with a more attractive and pleasing atmosphere, but also allowing people to maintain visual contact with the outside world. In recent years, greater recognition has been given to the contribution that daylight can make to energy conservation in buildings. From the energy- and cost-saving viewpoint, the arguments for daylight are strong. Energy savings resulting from daylighting mean not only low electric lighting and reduced peak electrical demands, but also reduced cooling loads and potential for smaller heating, ventilating and air-conditioning (HVAC) equipment size. It has been found that artificial lighting accounts for 20–30% of the total electricity use in fully air-conditioned multi-storey office buildings in Hong Kong [1]. Moreover, heat gain due to electric lighting represents a significant proportion of the total cooling load during the hot summer months.

Many studies indicate that proper lighting controls integrated with daylighting have a strong potential for reducing energy demand in non-domestic building by exploiting daylight more effectively [2,3]. New technologies such as daylight-linked photoelectric switching, time switching and localised manual control have been developed to enhance the efficient use of daylight [4]. However, daylight is always accompanied by solar heat gain. When the illuminance level exceeds the design requirement, the benefits from daylight will be penalised by the increased solar heat gains which will increase the cooling load. An integrated thermal and lighting model is therefore required. There exist some simple and very useful expressions for the estimation of energy savings from different types of photoelectric lighting controls [5–7]. Attempts have also been made to consider the trade-off between daylight-induced energy savings and extra heating requirements due to bigger glazing area, and hence larger heat loss in temperate climates [8]. The interactions and relationships between lighting, heating and in particular, cooling, and their implications for energy consumption in buildings are rather complex. Building energy simulation computer programmes, (e.g. DOE-2 [9]) are valuable design and analysis tools to evaluate the full benefits of daylighting by assessing the energy performance of the building envelope savings and cooling energy requirements [10,11]. However, discussions with local architects and engineers have revealed that most designers would prefer a simpler approach to assess the likely energy savings from daylighting and corresponding increases in solar heat gain through fenestration. Such methods would be particularly useful during the initial design stage when different design schemes and concepts are being developed [12]. This paper presents the work on a simple method which assesses the energy efficiency of fenestration systems in terms of the trade-off between daylighting and solar heat gain in cooling-dominated office buildings.

2. Measuring station

Data measurement is regarded as the most effective and accurate method of setting up the databases of solar radiation and outdoor illuminance. Horizontal solar data can be used in studying horizontal fenestration such as skylights. Nevertheless, there are greater demands for the knowledge of solar radiation and daylight level on vertical surfaces, particularly for high-rise buildings with large glazing areas. Measurements of the vertical solar radiation and daylight illuminance on the four cardinal surfaces facing the north, east, south and west have been made at the City University of Hong Kong since 1996. The measuring station is located on the rooftop of the City University of Hong Kong. The instrumentation consists of four pyranometers and four illuminance meters for the vertical solar radiation and daylight illuminance data measurements, respectively. All sensors are installed on the rooftop in a position relatively free from any external obstructions, and readily accessible for inspection and general cleaning. Data collection starts before sunrise and finishes after sunset. All measurements are referred to true solar time. The four pyranometers (CM11) manufactured by Kipp and Zonen of The Netherlands are used to carry out the measurement of global radiation on the vertical planes facing the north, east, south and west. Each pyranometer is connected to its own integrator (CC20) which measures the solar irradiance. The irradiance data are captured simultaneously twice per second, averaged over 10-min intervals and stored in two computers which are connected to the four integrators. The measurements of the global illuminance at the four cardinal orientations are made by means of the four illuminance meters which were manufactured and calibrated by Minolta of Japan. The four silicon photovoltaic cells incorporate cosine and colour correction. The measured results are converted into digital signals by an analogue/digital converter (12 bits A/D-D/A card) before feeding into a micro-computer for storage. Data are collected every 15 seconds, averaged over 5-min intervals.

3. Solar heat gain factors

It has been shown that solar heat gain factors (SHGFs) in W/m^2 for the vertical surface can be expressed as follows [13]:

$$\mathrm{SHGF} = H_v(\tau_b + N_i\alpha_b) + I_v(0.799 + 0.0544N_i) \tag{1}$$

where I_v is the sum of hourly diffuse and reflected radiation on the plane of the vertical glazing (W/m^2); H_v is the hourly direct beam radiation on the plane of the vertical glazing (W/m^2); N_i is the inward-flowing fraction of the absorbed radiation; τ_b is the transmittance of the reference glazing for direct beam radiation and α_b is the absorption of the reference glazing for direct beam radiation.

The inward flowing fraction of the absorbed radiation, N_i, can be expressed as:

$$N_i = h_i/(h_i + h_o) \tag{2}$$

where h_i and h_o are heat transfer coefficients of the inside and outside glazing surfaces, respectively (W/m^2 K).

Assuming still air (natural convection) inside, h_i of 8.29 W/m^2 K has been recommended for general building design [14] and this value was used to calculate N_i. To determine h_o, the approach proposed by Loveday and Taki [15] based on wind speed and direction was adopted. Transmittance and absorptance for direct radiation are a function of the incident angle of the solar beam relative to the surface. A fifth-order polynomial expressing these properties in terms of angle of incidence, θ, developed by Stephenson [16] was adopted. For the ASHRAE reference ordinary glazing, transmittance and absorption are presented as follows:

$$\tau_b = -0.00885 + 2.71235 \cos\theta - 0.62062 \cos^2\theta - 7.07329 \cos^3\theta + 9.75995 \cos^4\theta - 3.89922 \cos^5\theta \tag{3}$$

$$\alpha_b = 0.001154 + 0.77674 \cos\theta - 3.94657 \cos^2\theta + 8.57881 \cos^3\theta - 8.38135 \cos^4\theta + 3.01188 \cos^5\theta \tag{4}$$

Eq. (1) was used to determine the hourly vertical SHGFs (based on measured vertical solar radiation and wind data from 1996 to 1998) for the four principle vertical surfaces. Average hourly SHGFs were calculated for the nine-month cooling season (March–November) as follows:

$$\text{Average SHGF} = \left[\sum_{j=1}^{N}\left(\sum_{i=1}^{n}\text{SHGF}_{ij}\right)\right]/(10\ N) \tag{5}$$

where n is the number of daylight hours per day and N is the number of days in the averaging period.

As indicated in Eq. (5), the averaging was carried out over a 10-h day in order to obtain the solar heat gain easily. Although the summer period in Hong Kong runs from May to October (when the mean outdoor dry bulb temperature exceeds 25°C), most commercial buildings require cooling for a longer period, usually from mid-March to mid-November due to high internal loads such as people, electric lighting and office equipment. The nine-month cooling season (from March to November) is therefore recommended for estimating the total solar heat gain for commercial buildings. The average hourly SHGFs for the 9-month cooling season are 98, 146, 146 and 166 W/m^2 for the north, east, south and west vertical surfaces, respectively. Low SHGF indicates diffuse radiation is the major component of the solar radiation received, while high SHGF shows that solar heat gain is mainly due to direct radiation.

Total solar heat gain within the cooling season for any surface is simply given by:

$$Q = (\text{average SHGF } A_f \text{ SC } H)/1000 \tag{6}$$

where Q is the solar heat gain (kWh); A_f is the area of fenestration (m^2); SC is the glass shading coefficient; $H = 10 \times \text{N}$ is the total number of hours.

For office buildings with a $5\frac{1}{2}$-day working week, Q in Eq. (6) should be multiplied by a factor of 5.5/7.

4. Daylight availability

In the present study, 3-year (1996–1998) measured hourly vertical outdoor illuminance data, based on typical office hours of 08:00–18:00 (10-h working day) in Hong Kong were used for the analysis.

4.1. Frequency of occurrence

Graphical representation is a simple and direct approach to analyse and interpret measured weather data. It is also useful for climate assessment during the early building design stage. Fig. 1 shows the frequency of occurrence for the vertical global illuminance on unobstructed planes facing the north, east, south

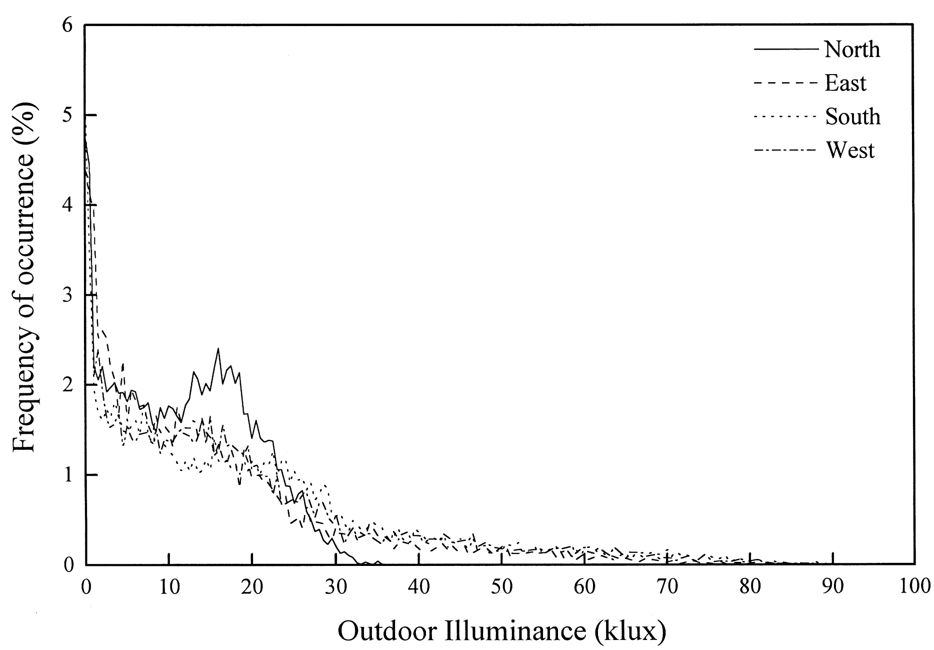

Fig. 1. Frequency of occurrence for outdoor illuminance on a vertical surface.

and west. These plots highlight the large differences which occur with orientation. The north-facing surface has a low daylight level and its maximum illuminance is around 35 klux. For the other vertical surfaces (i.e. E, S and W) they have very similar trends and their maximum illuminance levels are around 90 klux which is more than double the north-facing surface. High portions of the data are below 30 klux for all four vertical surfaces indicating that diffuse illuminance is the major component in this region.

4.2. Cumulative frequency distribution

Cumulative frequency distributions for the vertical illuminance on the four cardinal orientations were determined and are shown in Fig. 2. For illuminance less than 4 klux, no difference is found among the four surfaces. This corresponds to overcast conditions and the sky is nearly uniform. For high illuminance, which is often accompanied by direct sunlight, the effects of orientation are very significant. For example, a total illuminance of 25 klux or higher is exceeded for less than 5% for the north-facing surface, but this illuminance level is exceeded for about 20% of the year for the other orientations. It should be pointed out that the illuminance on the north surface is mainly diffuse and no shading device is required to exclude the direct sunlight. It is interesting to note that the north-

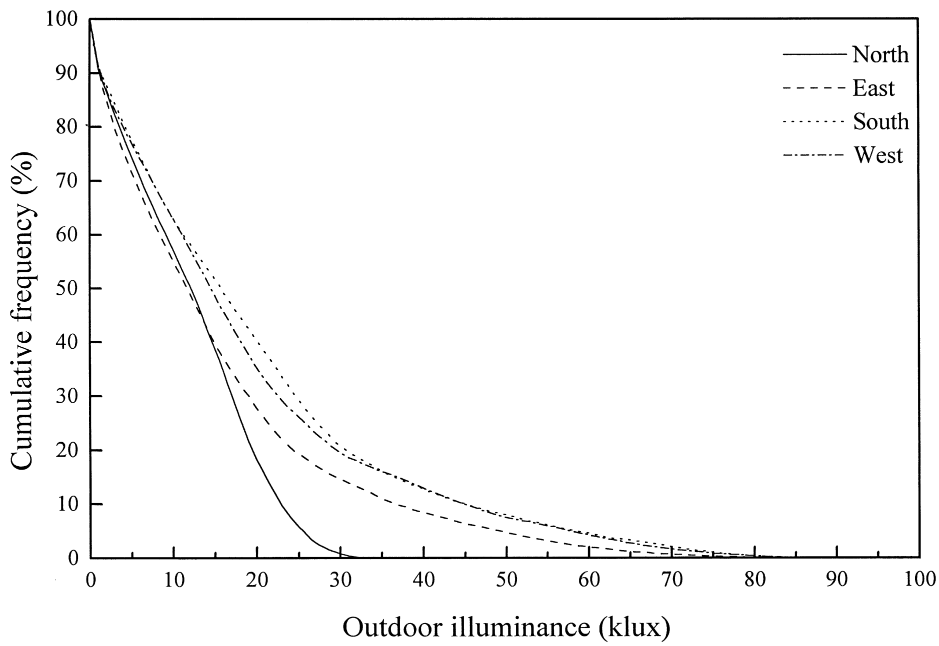

Fig. 2. Cumulative frequency distribution for outdoor illuminance on a vertical surface.

and east-facing surfaces are very similar at low illuminance (i.e. below 15 klux). This is mainly because a high portion of data are taken in the afternoon, and these data are 'diffuse-oriented' of low illuminance level for the east-facing surface.

5. Energy implications

For daylighting design and calculation, a cumulative frequency distribution of the outdoor illuminance can indicate the percentage of the working year in which a given illuminance is exceeded. It has been pointed out that vertical external illuminance can provide more accurate information than the horizontal one to determine the average indoor illuminance [17]. In a side-lit room, daylight may be more nearly proportional to the amount of daylight falling on the window, rather than to the external horizontal daylight illuminance. This approach uses the cumulative distribution of vertical illuminance on the window wall with a 'vertical daylight factor' to find out the internal illuminance distribution [18]. This is valuable for determining the necessary use of artificial lighting, and the probable energy savings for an on–off control. For a good approximation ignoring differential switching or dead band, the fraction of the working year that electric lighting would be off under an on–off control is simply given by the fraction of the working year that the daylight threshold illuminance level is exceeded. If the external vertical illuminance required to provide a certain indoor design illuminance is 10 klux, it can be seen from Fig. 2 that over 60% of the time in a year the daylight illuminance level can meet the criterion. In other words, over 60% of the time, daylighting alone would be adequate to achieve the required indoor design lighting level. This has significant implications for the energy efficiency in office building design in Hong Kong, where electric lighting accounts for 20–30% of the total electricity use and is a major component in total building cooling load [1].

6. Estimation of energy savings

The methods of controlling lighting energy consumption may be divided into two basic categories. The first type of control provides for either the on or off state, and the second allows the level to be set between maximum and minimum levels by dimming (top-up). An on–off control is designed to switch artificial lighting on and off automatically as the daylight level falls and rises respectively through a predetermined level. A variant of the on–off control is the 'differential switching' photoelectric control. Differential switching has two switching illuminances; one at which the lights are switched off, and another, at which the lights are switched on. The main advantage is that it can reduce rapid switching on and off when the illuminance swings around the desired level. The aim here is to get some idea about the likely energy savings. Therefore, for the sake of simplicity, only standard on–off control is considered in the present study.

A top-up control varies the light output of lamps in accordance with the prevailing daylight level. When daylight is inadequate to achieve the required design illuminance, it is topped up by artificial lighting. The fractional saving from a top-up control is equal to the fractional saving using an on–off control plus the extra fractional saving using a dimming system to 'top-up'. Assuming 12% of the total electric lighting energy is consumed by the control gear [6], the fraction of the working year when daylighting is adequate for a top-up control can be written as:

$$F_t = F_o + 0.88(I_o/E_o) \tag{7}$$

where F_t is the fraction of the working year when daylighting alone can achieve the required indoor design illuminance using top-up control; F_o is the fraction of the working year when daylighting alone can achieve the required indoor design illuminance using on–off control; I_d is the summation of the products of frequency f and its corresponding illuminance in mid-point of each 1 klux interval up to E_o; E_o is the required outdoor illuminance which will provide adequate indoor illuminance.

6.1. Vertical illuminance method

In the early days of illuminating engineering, all lighting designs and analyses were based on the point-by-point calculation method. In the 1920s, the lumen method was introduced but only for indoor artificial lighting designs. More recently, the concept of the average daylight factor, average over the working plane and average over all the interior surfaces was proposed for daylighting calculations for side-lit rooms [19,20]. This idea was further developed by Littlefair [18] to relate the average indoor daylight illuminance to the illuminance on an external vertical surface for the 'average sky' (this represents an average both over all the points in the room and over a range of sky conditions for a particular location) as follows:

$$\text{Light flux entering window} = E_v LTA_w \tag{8}$$

$$\text{Light flux absorbed by indoor surfaces} = E_{in}A_{in}(1-R) \tag{9}$$

where E_v is the vertical illuminance on the window (lux); E_{in} is the average illuminance on all the room surfaces (lux); LT is the light transmittance of glass; A_w is the window area (m^2); A_{in} is the total area of indoor surfaces (m^2); R is the area-weighted mean reflectance of all indoor surfaces.

From the law of conservation, light flux entering the room must be equal to the light flux absorbed by all the indoor surfaces. Hence, equating Eqs. (8) and (9), we have:

$$E_{in} = (A_w \mathrm{LT} E_v)/[A_{in}(1 - R)] \tag{10}$$

If E_{in} is assumed to be close to the indoor design illuminance on the working plane, then from Eq. (10) we can estimate the threshold vertical illuminance above which daylighting alone will be adequate to achieve the required indoor lighting level.

6.2. Daylighting energy savings

Using a vertical illuminance approach, the ratio of the indoor to outdoor vertical illuminance is a constant for a particular room design. More vertical daylight contributes a higher indoor illuminance level. The perimeter zone of a type of generic office building is considered. It is 35 × 35 m with four 4.5 m-deep perimeter zones. The floor-to-ceiling height is 2.4 m with an area-weighted mean reflectance of 0.5 for all the internal surfaces and fenestration area is 35 × 1.5 m for each orientation. To assess the potential energy savings due to daylighting, percentages of the working year when daylighting can provide adequate illuminance for different design illuminances and glass types were calculated. Figs. 3 and 4 present the potential energy savings for the south-facing surface under on–off and top-up controls, respectively. Calculations were based on the

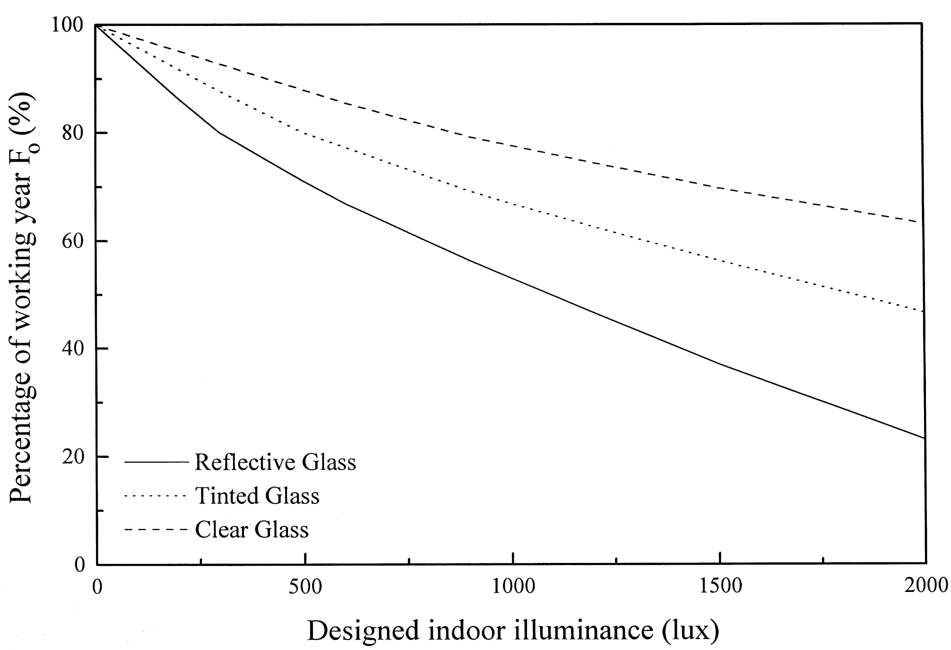

Fig. 3. Percentage of working year when daylighting alone can achieve the required indoor design illuminance for the south-facing surface using an on–off control.

cumulative frequency distribution for vertical illuminance shown in Fig. 2. It is believed that Figs. 3 and 4 can give a good indication of the general trend of how lighting energy savings would vary with different glass types and indoor design illuminances. Both the on–off and top-up controls enjoy high energy savings. With a 500 lux indoor design illuminance and an on–off control for the south-facing surface, about 71, 80 and 88% of the working year daylighting alone will be adequate for reflective, tinted and clear glass, respectively. For the top-up controls, daylighting availability is a few percentage points higher. Similar findings can be found for the other vertical surfaces.

Energy savings in electric lighting per year are given by:

$$E_a = \mathrm{LPD} A_f H_a F / 1000 \quad (11)$$

where E_a is the annual energy savings in electric lighting (kWh); LPD is the installed lighting power density (W/m^2); A_f is the floor area (m^2); H_a is the annual operating hours of the electric lighting system (hours); F is F_o (for on–off control) and F_t (for top-up control).

As mentioned earlier, air-conditioned office buildings in Hong Kong tend to have cooling requirements during the nine-month period from March to November. Total solar heat gain through the windows during the nine-month

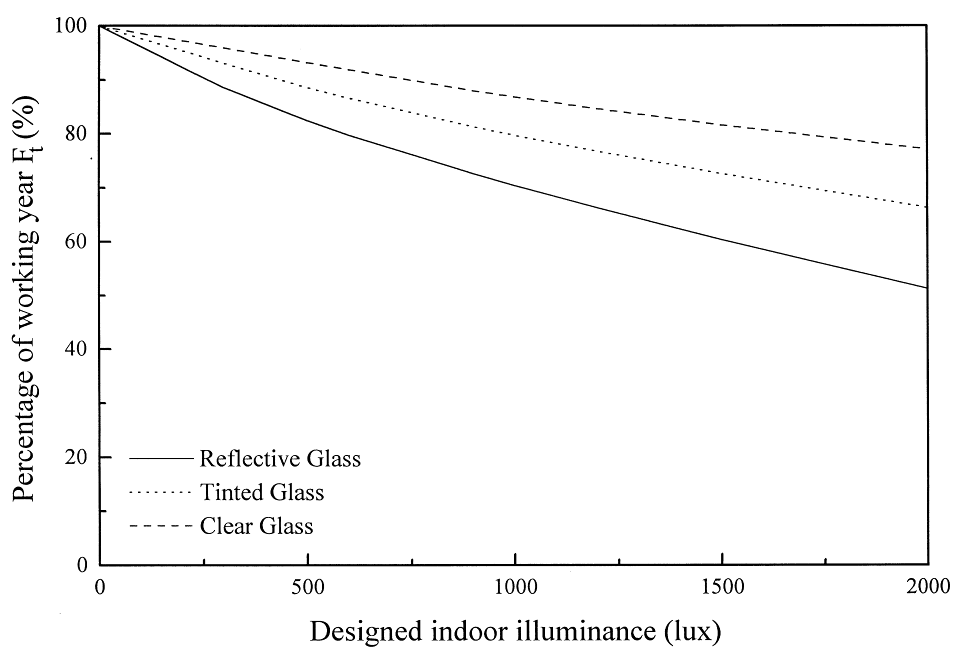

Fig. 4. Percentage of working year when daylighting alone can achieve the required indoor design illuminance for the south-facing surface using a top-up control.

period is given by Eq. (5), with the average SHGF and the averaging period corresponding to the nine-month cooling season. Electric lighting energy savings during the cooling season are given by the following equation:

$$E_c = \mathrm{LPD} A_f H_c F_c / 1000 \tag{12}$$

where E_c is the electric lighting energy saving during the cooling season (kWh); H_c is the total hours of operation of electric lighting during the cooling season (hour); F_c is the fraction of the working cooling season when daylighting alone can achieve the required indoor design illuminance; F_c is F_{oc} (for on–off control) and F_{tc} (for top-up control).

Values of F_{oc} and F_{tc} were calculated for different glass types and indoor design illuminance and those for south-facing surfaces are shown in Figs. 5 and 6. Similar results were determined for other vertical surfaces. The general trends and features of Figs. 5 and 6 are very similar to those shown in Figs. 3 and 4 for the whole year with the former being slightly higher than the latter. This suggests that there is more daylight during the nine-month cooling season than during the winter months from December to February.

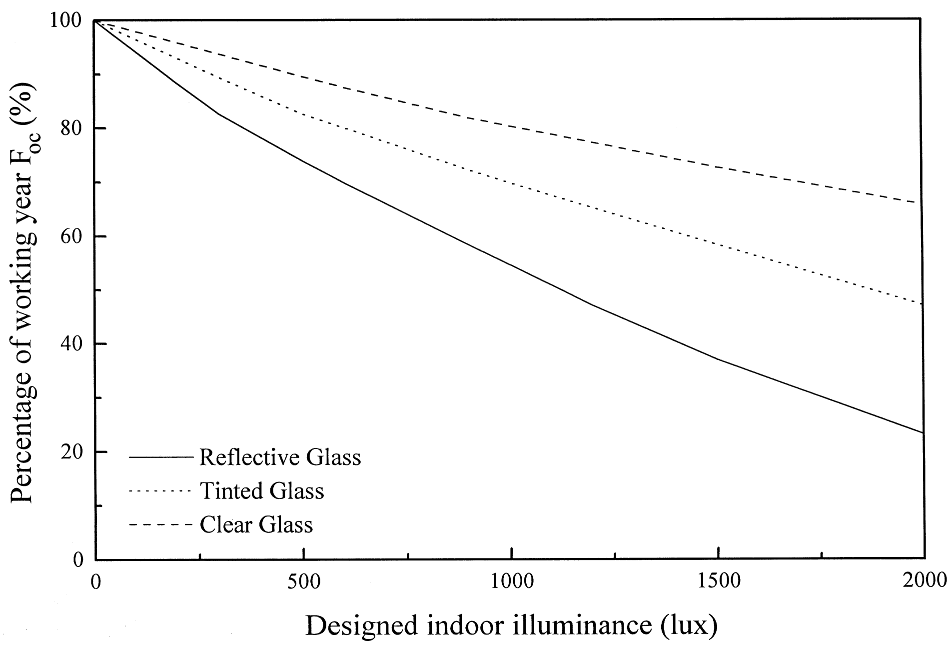

Fig. 5. Percentage of working cooling season when daylighting alone can achieve the required indoor design illuminance for the south-facing surface using an on–off control.

7. Worked examples

The application of this simple estimation method can best be illustrated with worked examples. This can also give a feel for the likely magnitude of energy savings when using daylighting schemes in Hong Kong. The examples are based on a generic office building described earlier with the following assumptions:

1. a light transmittance of 0.3 and a shading coefficient of 0.4 for typical reflective glass used in commercial buildings in Hong Kong;
2. an area-weighted mean reflectance of 0.5 for the internal surfaces;
3. no external obstruction;
4. an indoor design illuminance of 500 lux with a typical installed lighting load of 20 W/m^2 of floor area;
5. a 10-h working day (08:00–18:00) and a $5\frac{1}{2}$-day working week.

Eq. (11) was used to estimate the annual energy savings in electric lighting fractions of the working year when daylighting alone could achieve the required indoor design illuminance. Values of F_o and F_t were obtained from Figs. 3 and 4 with a 500 lux indoor design illuminance. Eqs. (6) and (12) were used to calculate the solar heat gain and the reduction in sensible heat from electric lighting during the nine-month cooling season.

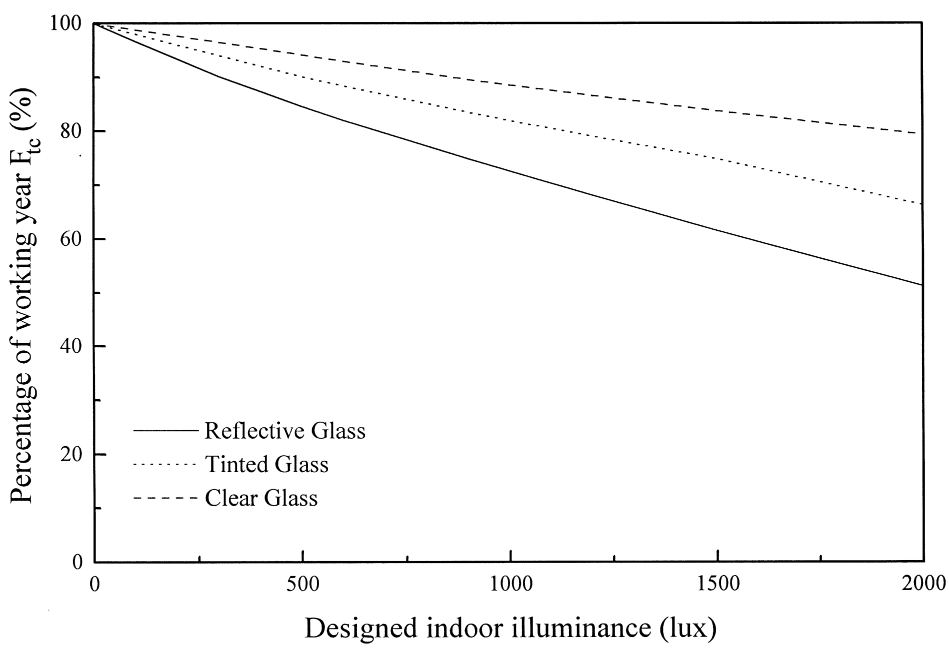

Fig. 6. Percentage of working cooling season when daylighting alone can achieve the required indoor design illuminance for the south-facing surface using a top-up control.

Three examples are presented. Example 1 compares two designs — one with daylighting controls and the other without. Tables 1 and 2 show the estimated energy savings for using the on–off and top-up controls, respectively. It can be seen that the estimated energy savings are quite substantial. Table 1 indicates that electricity savings for artificial lighting are very similar, ranging from 38.1 kWh/m^2 for the north perimeter office to 40.6 kWh/m^2 for the south perimeter office. The overall effect of incorporating daylighting is the reduction of electric energy use of 48.2 kWh/m^2 per year for the perimeter zones. Similar features are observed for the top-up controls shown in Table 2. On average, top-up controls have about 8.7 kWh/m^2 more electric energy savings than on–off controls. These figures, however, should only be regarded as an indication of the likely magnitude of energy savings. In Hong Kong, most building development projects are close to each other and hence external obstructions can be severe. It is therefore envisaged that the energy savings will be less than those shown in Tables 1 and 2. Nevertheless, it is believed that energy savings can still be significant.

Example 2 considers the effect of increasing the window size. Table 3 summaries the effects of changing the window-to-wall ratio (WWR) to 70%. Top-up controls were assumed for both designs. It can be seen that the increase in solar heat gain ranges from 17.3 kWh/m^2 for the north perimeter office to 29.3 kWh/m^2 for the west perimeter office, with a mean value of 24.6 kWh/m^2. The larger window area provides more natural light and results in a slight reduction in the amount of sensible heat gain from the electric lighting system. The overall effect is an increase of 1.3 kWh/m^2 for the north-facing office to 6 kWh/m^2 for the west-facing office.

Example 3 assesses the consequence of using tinted glass with a shading coefficient of 0.7 and a light transmittance of 0.5, instead of the reflective glass considered in examples 1 and 2. Again, top-up controls were assumed. Table 4 shows the findings. A higher light transmittance allows more daylight and hence less electricity consumption for artificial lighting and bigger reduction in sensible heat gain from electric lights compared with the reflective glass. However, tinted glass admits more solar heat and the overall effect is an increase of electricity use of 5.7 kWh/m^2 per year for the perimeter offices.

Table 1
Estimated annual electricity savings/penalty for on–off controls

	North	East	South	West	Mean kWh/m^2
(a) Increase in solar heat gain	0	0	0	0	0
(b) Reduction in sensible heat gain from artificial lights	27.2	26	28.5	29	27.7
(c) Electricity savings/penalty in cooling[a], [(b)−(a)]/3[b]	9.1	8.7	9.5	9.7	9.3
(d) Electricity savings in artificial lighting	38.2	36.8	40.8	40.7	39.1
(e) Overall electricity savings/penalty[a], (c) + (d)	47.3	45.5	50.3	50.4	48.4

[a] Negative indicates penalty.
[b] Assumes an average coefficient of performance of 3 for the chiller plants.

Table 2
Estimated annual electricity savings/penalty for top-up controls

	North	East	South	West	Mean kWh/m^2
(a) Increase in solar heat gain	0	0	0	0	0
(b) Reduction in sensible heat gain from artificial lights	31.8	31	32.6	32.7	32
(c) Electricity savings/penalty in cooling[a], [(b)−(a)]/3[b]	10.6	10.3	10.9	10.9	10.7
(d) Electricity savings in artificial lighting	45.9	44.7	47.3	47.1	46.3
(e) Overall electricity savings/penalty[a], (c) + (d)	56.5	55	58.2	58	56.9

[a] Negative indicates penalty.
[b] Assumes an average coefficient of performance of 3 for the chiller plants.

8. Conclusions

Three-year (1996–1998) measured solar radiation and outdoor illuminance data have been gathered and analysed. The north-facing surface mainly receives a diffuse component of low measured values, while the other vertical surfaces receive a certain amount of direct components, resulting in higher measured values. The cumulative frequency distribution of the outdoor illuminance can provide valuable information on the predication of the probable electric lighting savings. In subtropical Hong Kong, over 60% of the time, indoor illuminance can be provided by daylight if the required external vertical illuminance is 10 klux. The daylight-induced cooling penalty for different daylighting schemes using the average solar heat gain factors has been proposed. Based on the measured vertical data, sets of curves to predict electric energy savings under the on–off and top-up controls have been presented for different glass types and indoor design illuminances. These simple curves are useful for assessing different daylighting schemes during the initial design stage. Worked examples based on a generic reference office building indicate that energy savings in electric lighting can be in the order of 40–60 kWh/m^2 per year for the perimeter zones if daylighting schemes with on–off and top-up controls are incorporated in the architectural and building design. It is hoped that the method presented can help architects and

Table 3
Estimated annual electricity savings/penalty for larger window areas

	North	East	South	West	Mean kWh/m^2
(a) Increase in solar heat gain	17.3	25.8	25.8	29.3	24.6
(b) Reduction in sensible heat gain from artificial lights	2.2	2.4	2	1.8	2.1
(c) Electricity savings/penalty in cooling[a], [(b)−(a)]/3[b]	−5	−7.8	−7.9	−9.2	−7.5
(d) Electricity savings in artificial lighting	3.7	3.9	3.2	3.2	3.5
(e) Overall electricity savings/penalty[a], (c) + (d)	−1.3	−3.9	−4.7	−6	−4

[a] Negative indicates penalty.
[b] Assumes an average coefficient of performance of 3 for the chiller plants.

Table 4
Estimated annual electricity savings/penalty for using tinted glass instead of reflective glass

	North	East	South	West	Mean kWh/m^2
(a) Increase in solar heat gain	21.6	32.3	32.3	36.7	30.7
(b) Reduction in sensible heat gain from artificial lights	2.4	2.6	2.1	2	2.3
(c) Electricity savings/penalty in cooling[a], [(b)−(a)]/3[b]	−6.4	−9.9	−10.1	−11.6	−9.5
(d) Electricity savings in artificial lighting	4	4.3	3.5	3.5	3.8
(e) Overall electricity savings/penalty[a], (c)+(d)	−2.4	−5.6	−6.6	−8.1	−5.7

[a] Negative indicates penalty.
[b] Assumes an average coefficient of performance of 3 for the chiller plants.

building engineers assess the relative energy performance of different design schemes and estimate the likely energy benefits or penalty during the initial design stage. Although the work presented is based on the Hong Kong environment, it is believed that the methodology and procedures outlined can be applied to other cooling-dominated buildings, particularly in the tropical and subtropical regions.

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